1. **Project Name:** **Virtual Welded-Joint Design Integrating Advanced Materials and Processing Technologies**

2. **Lead Organization:** Caterpillar Inc.
Technical Service Division
Peoria, IL 61656-1875

3. **Principal Investigator:**
Zhishang Yang
Phone: (309) 578-2761
Fax: (309)578-3322
Email: Yang_Zhishang@cat.com

4. **Project Partners:** Battelle Memorial Institute, subcontract
Colorado School of Mines, subcontract
Oak Ridge National Laboratory, DOE field proposal
QuesTek Innovations, LLC, subcontract
The Pennsylvania State University, subcontract

5. **Date Project Initiated and FY of Effort:** October 1, 2001and Year 2

6. **Expected Completion Date:** September 30, 2004

7. **Project Technical Milestones and Schedule:**

M1. Weld Thermo Fluid Model (WTFM)	Plan	Actual
T1. Development of 3-D Free Surface Weld Pool Model	9/30/2002	Completed
T2. Weld Zone Composition Prediction	6/30/2003	50% Completed
T3. Weld Consumable Design Optimization	9/30/2003	70% Completed
M2. Weld Microstructural Model (WMM)		
T4. Grain Size and Phase Transformation Prediction	6/30/2003	80% Completed
T5. Consumable Design for High Alloy Composition	9/30/2003	70% Completed
T6. Inclusion Formation Prediction	12/30/2003	20% Completed
T7. Laser Welding of Higher Strength Materials - Microstructure	3/30/2004	NO-GO?
M3. Weld Property Model (WPM)		
T8. Relation of microstructure-property at room temperature	12/30/2002	80% Completed
T9. Determination of Stress-Strain Curves at Elevated Temperature	3/30/2003	50% Completed
T10. Development of Weld Material Property Model	9/30/2003	30% Completed
T11. Laser Welding of Higher Strength Materials - Property	12/30/2003	NO-GO?
M4. Weld Structural Model (WSM)		
T12. Further Development of 3-D Residual Stress Modeling	6/30/2003	50% Completed
T13. Residual Stress Measurements	12/30/2003	
T14. Model Verification and Refinement	9/30/2003	20% Completed
M5. Weld Fatigue Model (WFM)		
T15. Crack Nucleation	9/30/2002	In progress
T16. Small Crack Growth	3/30/2003	In progress
T17. Paris Law Dominated Crack Growth	6/30/2003	30% Completed
T18. Model Integration and Parametric Study	12/30/2003	
T19. Component Fatigue Demo Test	9/30/2004	
M6. Integration (I)		
T20. Incorporation of Thermal History from WFTM into WMM	3/30/2002	90% Completed
T21. Incorporation of Thermal History from WFTM into WSM	6/30/2003	50% Completed
T22. Incorporation of Phase Transformation and WPM into WSM	9/30/2003	50% Completed
T23. Incorporation of WMM and WPM into WFM	12/30/2003	30% Completed
T24. Incorporation of Residual Stress into WFM	12/30/2003	30% Completed
T25. Case Studies	3/30/2004	
M7. Technology Demonstration - Proof of Concepts		
T26. Technology Demo	9/30/2004	30% Completed
M8. Project Administration		
T27. Program Management		
T28. Reporting and Technology Transfer		

8. **Past Project Milestones and Accomplishments:**

Module 1 Weld Thermo-Fluid Model (WTFM)

- A 3D weld thermo-fluid model with free surface has been developed to simulate weld pool formation for Gas-Metal-Arc welding.
- The model has been applied to predict weld bead shape for different types of welded-joints including butt welds, T-fillet welds, and plug welds.

Module 2: Weld Microstructure Model (WMM)

- The capabilities to predict the spatial evolution of weld microstructure such as phase transformations and grain growth in both weld fusion zone and its heat-affected zone (HAZ) have been established.
- The capability of microstructure model to predict phase transformations in weld fusion zone has been validated by comparing the predicted results with experimental results.

Module 3: Weld Material Property Model (WMPM)

- The true stress-strain curves for two steels at both ambient and elevated temperatures have been tested using Gleeble machine at Oak Ridge National Laboratory. The data will be used to develop WMPM.

Module 4: Weld Structural Model (WSM)

- The formulation of user material subroutine for structural analysis (UMAT) incorporating phase transformation effects has been completed.
- Ufield mapping has been completed to map externally generated microstructure phase volume fractions onto ABAQUS field variables.

Module 5: Weld Fatigue Model (WFM)

- The mesh-insensitive structural stress methods have been used to analyze the effect of welding residual stress on weld fatigue strength.
- A two-stage growth model is being developed to investigate the threshold effects. Crack nucleation and short crack growth are being treated as a continuum in the crack growth regime.

Module 6: Model Integration

- Part of the integration of the sub-models has been done. The integration includes integration of thermal history from thermal model for microstructure prediction.
- Integrate the weld bead shape from Weld Thermo-Fluid Model, which has a small computation domain due to extensive computation involved in CFD, into Finite Element Analysis (FEA).

Module 7: Technology Demo

- The developed models have been used to guide the design of a special welding consumable. This consumable is being developed to generate compressive residual stress at the weld toe by the expansion of volume due to low temperature martensite transformation.
- Preliminary experimental results indicated about 10x weld fatigue strength improvement by the combination of desired weld bead shape and compressive residual stress at weld toe.

9. **Planned Future Milestones:**

Module 1 Weld Thermo-Fluid Model (WTFM)

- The model will be further developed to predict the composition in weld fusion zone considering the mixture of the metal droplets from welding consumable with the base material. (06/30/2003)
- Parametric study to test the model's capabilities to predict weld bead shape and weld composition. (09/30/2003)

Module 2: Weld Microstructure Model (WMM)

- Prediction of grain growth in HAZ of HSLA steels considering the effect of particle pinning on grain growth. (06/30/2003)
- The weld pool inclusion formation model. (09/30/2003)

Module 3: Weld Material Property Model (WMPM)

- More Gleeble tests will be done to obtain the true stress-strain curves at elevated temperatures for both mild and HSLA steels. (07/30/2003)

- The WMPM model will be developed based on Gleeble test results in combination with data available in literature. (09/30/2003)
  Module 4: Weld Structural Model (WSM)
- The effect of phase transformation on residual stress formation will be incorporated into an existing user material subroutine (UMAT). (07/30/2003)
- The model will be calibrated based on experimental data. (09/30/2003)
  Module 5: Weld Fatigue Model (WFM)
- The weld residual stresses will be quantified based on the mesh-insensitive structural stress methods. (09/30/2003)
- Theoretical formulation will be developed to rephrase the two-stage growth model in terms of both ? K and K_{max} to investigate the threshold effects. Crack growth data at short crack regime in welded joints will be evaluated. (12/30/2003)
  Module 6: Model Integration
- Commerical softwares will be evaluated for the integration of the individual models (12/30/2003)
- Case studies using the integrated model (03/30/2004)
  Module 7: Technology Demo
- The integrated model will be used for design of high performance welded joints considering the combined effects of weld bead shape, microstructure, material properties, residual stress, and fatigue strength. (06/30/2004)
- A small scale fabricated structure using high strength steel will be made based on the simulation results from Virtual Welded-Joint Design.(09/30/2004)

10. **Issues/Barriers:**

Modeling weld bead formation for Gas-Metal-Arc welding is an extremely challenging task considering the interaction of metal droplets from consumable with the weld pool. In addition, the surface of the weld pool keeps changing due to the deposition of consumable. Commercial CFD software, FLOW3D, was selected as a solver in this task due to its excellent capability to handle free surface without tedious work on meshing. FLOW3D had not been applied for welding simulation before this project. Customized subroutines have been written in this project to considering the unique features in weld pool simulation.

The task of relating microstructure to property relies on experimental measurement of stress strain characteristics at different temperatures. During the research, Caterpillar and ORNL researchers found the local soft zone that forms at low temperature away from the peak temperature location, prevented the measurement of stress-strain curves at temperatures lower than 500°C. This technical barrier indeed slowed our progress to certain extent. The technical issue was solved by adopting compressive test mode and modified specimen geometry.

Two major issues are to be resolved in fatigue life prediction models incorporating both residual stresses and short crack growths. A mechanics based quantitative relationship between weld residual stress and fatigue life is nonexistent before this project. The major difficulty lies in the fact that the welding induced residual stresses can be highly complex at fatigue prone locations, coupled with severe stress concentration due to external loading. This major hurdle can be overcome by considering a broad spectrum of fatigue data collected not only using PWHT stress relief and weld sequencing. The earlier crack growth and notch effects on life have been a hotly debated subject area and can be viewed as a major barrier in reliable fatigue life design, particularly for the welded structure community. This is in part due to the fact that notch stresses are difficult to estimate for welded joints. With the recent advance in mesh-insensitive structural stress procedures, we anticipate to make a major progress in this area by the end of Year 2 of this project.

11. **Intended Market and Commercialization Plans/Progress:**

So far, seven presentations have been made in international conferences and 2 technical papers have been published in conference proceedings to diffuse the developed technologies into other industries. We have got many positive responses from people working on welding research. In the next step, an advisory committee including different IOF industries will be formed for more effective diffusion of the technologies into IOF industries. It is planed to have two commercialization meetings with the advisory committee participation. One meeting is planed in the end of year 2 of this project after individual models have been established. This meeting will be held to discuss how the developed suite of welding simulation tools can be beneficial for industrial applications. The second meeting will be held in the end of this project. By that time, the individual models will have been integrated. A technical demonstration will be made to show how the integrated model can be used for systematic design of high performance welded-joints. Fabricated structure using high strength steel will be made based on the results from Virtual Welded-Joint Design.

12. **Patents, publications, présentations:**

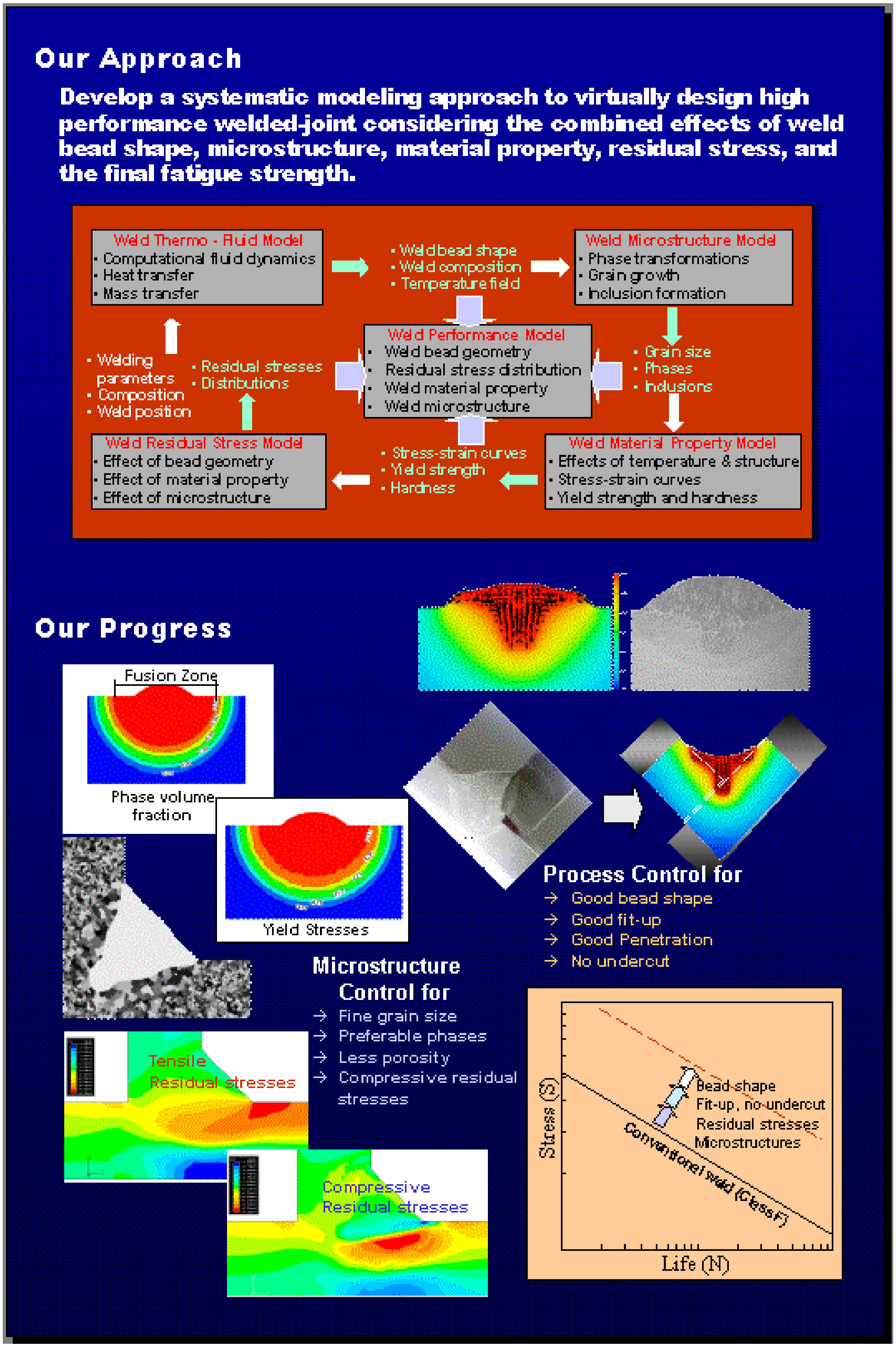
Publications:

- Z. Yang, X. L. Chen, N. Chen, H. W. Ludewig and Z. Cao: "Virtual Welded-Joint Design by Coupling Thermal-Metallurgical-Mechanical Modeling", *Proceedings of 6th Intl. Conf. On Trends in Welding Research*, Pine Mountain, GA, April 2002.
- Z. Cao, Z. Yang, L. X. Chen and F. W. Brust: "Three-Dimensional Transient Weld Pool Simulation of Gas Metal Arc Welding", in Proceedings of the 2002 International Conference on Computational Engineering and Sciences, ICES 2002, Reno.

Presentations:

- Z. Yang, X. L. Chen, N. Chen and Z. Cao: "Virtual Welded-Joint Design – A Systematic Modeling Approach for High Performance Welds", 84th Annual Convention, Detroit, April 2003.
- Z. Yang, X. L. Chen, N. Chen and Z. Cao: "A Systematic Microstructure-Level Modeling Approach For Designing High Performance Welded-Joint", in 2002 Max Intl. AWS Welding Show and 83rd Annual Convention, Chicago, March 2002.
- Z. Cao, F. Brust, X. L. Chen, and Z. Yang: "Numerical Simulation of A 3-D Transient GMA Weld Pool", ibid.
- Z. Yang, X. L. Chen, N. Chen, H. W. Ludewig and Z. Cao: "Virtual Welded-Joint Design by Coupling Thermal-Metallurgical-Mechanical Modeling", in 6th Intl. Conf. On Trends in Welding Research, Pine Mountain, GA, April 2002
- Z. Yang, X. L. Chen, N. Chen, H. W. Ludewig and Z. Cao: "A Systematic Approach for Virtual Welded-Joint Design", PVP 2002.
- Effects of Manganese and Nickel on the Phase Stability of High Alloy Weld Metals, F. Martinez, G. Edwards, and S. Liu,. Presented at the AWS Welding Show 2003, April 8th, 2003, Detroit, Michigan, High Alloy Weldments for Fatigue Resistance in Structural Carbon Steel.
- F. Martinez, G. Edwards, and S. Liu presented at the AWS Welding Show 2002,. March 5th, 2002, Chicago, Illinois

Highlight


Our Approach
Develop a systematic modeling approach to virtually design high performance welded-joint considering the combined effects of weld bead shape, microstructure, material property, residual stress, and the final fatigue strength.
Weld Thermo - Fluid Model
• Computational fluid dynamics
• Heat transfer
• Mass transfer
• Weld bead shape
• Weld composition
• Temperature field
Weld Microstructure Model
• Phase transformations
• Grain growth
• Inclusion formation
Weld Performance Model
• Weld bead geometry
• Residual stress distribution
• Weld material property
• Weld microstructure
• Welding parameters
• Composition
• Weld position
• Residual stresses
• Distributions
• Grain size
• Phases
• Inclusions
Weld Residual Stress Model
• Effect of bead geometry
• Effect of material property
• Effect of microstructure
• Stress-strain curves
• Yield strength
• Hardness
Weld Material Property Model
• Effects of temperature & structure
• Stress-strain curves
• Yield strength and hardness
Our Progress
Fusion Zone
Phase volume fraction
Yield Stresses
Process Control for
→ Good bead shape
→ Good fit-up
→ Good Penetration
→ No undercut
Microstructure Control for
→ Fine grain size
→ Preferable phases
→ Less porosity
→ Compressive residual stresses
Tensile Residual stresses
Compressive Residual stresses
Stress (S)
Life (N)
Bead shape
Fit-up, no undercut
Residual stresses
Microstructures
Conventional weld (Class F)